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Thermal stability of superconductors under the effect of a two-dimensional hyperbolic heat conduction model

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Abstract *The thermal stability of superconductor is numerically investigated under the effect of a two-dimensional hyperbolic heat conduction model. Two types of superconductor wires are considered, Types II and I. The thermal stability of superconductor wires under the effect of different design, geometrical and operating conditions is studied. The Effect of the time rate of change of the disturbance and the disturbance duration time is investigated. Generally, it is found that wave model predicts a wider stability region as compared to the predictions of the classical diffusion model.*

Nomenclature

A = conductor cross sectional area, m^2
B = dimensionless disturbance intensity, $\frac{T_i - T_0}{T_c - T_0}$
Bi = Biot number, $\frac{2h\sqrt{\alpha\tau_q}}{k}$
C = heat capacity, $\mathrm{J\,m^{-3}K^{-1}}$
d = conductor diameter, m
f = volume fraction of the stabilizer in conductor
g = Joule heating, $\mathrm{W\,m^{-3}}$
g_{max} = maximum joule heating with the whole current in the stabilizer, $\frac{\rho_0 J^2}{P}$, $\mathrm{W\,m^{-3}}$
G_{max} = dimensionless maximum joule heating, $\frac{4\tau_q\ g_{max}}{C(T_c - T_0)}$
h = convective heat transfer coefficient, $\mathrm{W\,m^{-2}K^{-1}}$
J = current density, $\mathrm{A\,m^{-2}}$
k = thermal conductivity of conductor, $\mathrm{W\,m^{-1}K^{-1}}$
$2l$ = length of conductor subjected to heat disturbances, m
L = Dimensionless disturbance length, $\frac{l}{2\sqrt{\alpha\tau_q}}$
P = conductor perimeter, m
$\mathbf{q}$ = conduction heat flux vector, $\mathrm{W\,m^{-2}}$
Q = dimensionless joule heating source, $\frac{4\tau_q g(T)}{C(T_c - T_0)}$,
R = Superconductor wire radius, m

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t = time, s
T = temperature, K
T_c = critical temperature, K
T_{c1} = current sharing temperature, K
T_i = initial temperature, K
$\dot{T}_i$ = time rate of change of initial temperature, Ks^{-1}
T_0 = ambient temperature, K
x = axial coordinate, m
r = Radial coordinate, m

Greek symbols
α = thermal diffusivity, K/C
β = dimensionless time, $\frac{t}{2\tau_q}$
η = dimensionless radial location, $\frac{r}{2\sqrt{\alpha\tau_q}}$
η_0 = dimensionless superconductor radius, $\frac{R}{2\sqrt{\alpha\tau_q}}$
δR = Radius of the conductor subjected to heat disturbances, m
θ = dimensionless temperature, $\frac{T-T_0}{T_c-T_0}$
θ_{c1} = dimensionless current sharing temperature, $\frac{T-T_0}{T_c-T_0}$
θ_1 = dimensionless maximum temperature, $\frac{T(t,0)-T_0}{T_c-T_0}$
$\dot{\theta}_i$ = dimensionless time rate of change of initial temperature, $\frac{T_i-T_0}{T_c-T_0}$
ξ = dimensionless axial location, $\frac{x}{2\sqrt{\alpha\tau_q}}$
ρ_0 = stabilizer electrical resistivity,
τ_i = dimensionless duration time, $\frac{t_i}{2\tau_q}$
τ_q = relaxation time of heat flux, s

Subscripts
i = initial
c1 = current sharing
max = maximum
0 = ambient

1. Introduction

Knowledge on the thermal stability and quench characteristics of superconducting wires are essential to the design and performance of superconducting devices used in electronic applications and in electric power transmission cables. These devices must be designed in such a way that they are stable against thermal disturbances. For example, a tiny conductor motion can initiate a normal zone in a high current density magnet. Other examples of disturbances are absorption of particulate or infrared radiation, or short-term failure of cooling. Disturbances immediately transform into heat pulses that increase the temperature of the superconductor. Thermal stability denotes a situation where a superconductor can carry the operating current without resistance at all times even if a localized thermal disturbance has been released.

In the literature, numerous researchers (Bejan and Tien, 1978; Abeln *et al.*, 1993; Malineowski, 1991, 1993, 1999; Maddock *et al.*, 1969; Seol and Chyu, 1994; Bellis and Iwasa, 1994; Ünal *et al.*, 1993; Ünal and Chyu, 1995 and Ptandhan *et al.*, 1995) have investigated the superconductor thermal stability using different superconductor types, geometries, assumptions, applications, operating conditions, and different models. Most previous work has investigated the superconductor stability under the effect of the parabolic heat conduction model, and very few of them have investigated the stability under the effect of the one-dimensional hyperbolic heat conduction model (Malineowski, 1999 and Al-Nimr *et al.*, 2002). Based on the authors' knowledge, the superconductor thermal stability under the effect of a two-dimensional hyperbolic heat conduction model (that considers the formation and behavior of a normal zone in both transverse and the longitudinal directions) has not been investigated. This is the objective of the present work. The investigation considers the stability of Type I and II superconductors under different operating, design, and geometrical parameters. Also, the effect of the time rate of change of the disturbance initial temperature and the disturbance duration on the super conductor will be investigated.

2. Analysis

Consider a thick superconductor cylinder or wire of infinite length carrying an electric current as shown schematically in Figure 1. A conductor section of length $2l$ is subjected to a centrally located instantaneous disturbance heat source of finite area $(\pi(\delta R)^2 \times 2l)$, thus this section will be heated up to a temperature T_i, exceeding the critical superconductor temperature T_{c1} at a given current. The superconductor may be of Type I or II. In Type I the superconductor is a non-composite type while in type II the superconductor consists of a superconducting strands (filaments) embedded in a high purity metal matrix. The superconductor is cooled via a cooling liquid surrounding the domain. The temperature field in the normal zone and the quenching process are governed by the energy conservation equation coupled with the two-dimensional hyperbolic heat conduction constitution law. Based on the assumption of constant properties, the governing equations are given as:

$$C\frac{\partial T}{\partial t} = k\nabla \mathbf{q} + g(x,r,t) \tag{1}$$

$$\mathbf{q}(x,r,t) + \tau_q \frac{\partial \mathbf{q}(x,r,t)}{\partial t} = -k\nabla T(x,r,t) \tag{2}$$

Eliminating the heat flux $\mathbf{q}$ between equations (1) and (2), leads to the following two-dimensional hyperbolic heat conduction equation

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} + \frac{\tau_q}{\alpha}\frac{\partial^2 T}{\partial t^2} = \frac{k}{r}\frac{\partial T}{\partial r} + k\frac{\partial^2 T}{\partial r^2} + k\frac{\partial^2 T}{\partial x^2} + g(x,r,t) + \tau_q \frac{\partial g(x,r,t)}{\partial t} \tag{3}$$

which transmits wave of temperature with a finite speed equal to (α/τ_q).

The steady capacity of the Ohmic heat source is given as

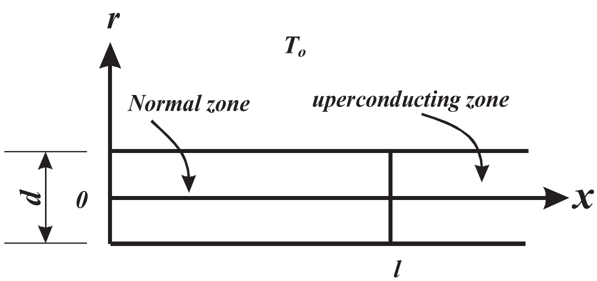

Figure 1. Schematic diagram for the problem under consideration

For Type I superconductor:

$$\begin{aligned} g(T) &= 0 && \text{for} \quad T \leq T_{c1} \\ g(T) &= g_{max} && \text{for} \quad T \geq T_{c1} \end{aligned} \tag{4}$$

and for Type II superconductor:

$$\begin{aligned} g(T) &= 0 && \text{for} \quad T \leq T_{c1} \\ g(T) &= \frac{g_{max}}{f}\frac{T - T_{c1}}{T_c - T_{c1}} && \text{for} \quad T_{c1} < T < T_{c1} \\ g(T) &= \frac{g_{max}}{f} && \text{for} \quad T \geq T_{c1} \end{aligned} \tag{5}$$

Due to the symmetry of the normal zone, the analysis is limited to the half zone, i.e., to the domain that lies within $x \geq 0$ and $0 \leq r \leq R$, where R is the superconductor wire radius ($R = d/2$). Equation (3) assumes the following initial and boundary conditions:

$$\begin{aligned} & T(x, r, 0) = T_i && \text{for} \quad 0 < x \leq l, \;\; 0 \leq r \leq \delta R \\ & T(x, r, 0) = T_0 && \text{for} \quad x > l \;\text{ and }\; \delta R \leq r \leq R \\ & \frac{\partial T(x, r, 0)}{\partial t} = T, && \text{for} \quad 0 \leq x \leq \infty \;\text{ and }\; 0 \leq r \leq R \\ & \frac{\partial T(0, r, t)}{\partial t} = 0, && T(\infty, r, t) = T_0 \\ & \frac{\partial T(x, 0, t)}{\partial t} = 0, && k\frac{\partial T(x, 0, t)}{\partial t} = -h(T - T_0) \end{aligned} \tag{6}$$

The above boundary conditions feature convective cooling on the surface and symmetry at the center of the conductor. The above initial conditions is based on the assumption that the disturbance energy is initially deposited in a centrally located cylindrical region of $\pi(\delta R)^2 \times 2l$. The length of the cylindrical heat source $2l$is variable, with a value closed to zero simulating a point heat source and a very large value simulating an infinitely long heat source.

It is more convenient to rewrite equations (3)–(6) using the following dimensionless parameters:

$$\xi = \frac{x}{2\sqrt{\alpha\tau_q}}, \qquad \beta = \frac{t}{2\tau_q}, \qquad \theta = \frac{T - T_0}{T_c - T_0}$$

$$\eta = \frac{r}{2\sqrt{\alpha\tau_q}}, \qquad Q = \frac{4\tau_q g(T)}{C(T_c - T_0)}, \qquad Bi = \frac{2h\sqrt{\alpha\tau_q}}{k},$$

$$L = \frac{l}{2\sqrt{\alpha\tau_q}}, \qquad \eta_0 = \frac{R}{2\sqrt{\alpha\tau_q}}, \qquad B = \frac{T_i - T_0}{T_c - T_0}$$

As a result, equation (3) is reduced to

$$\frac{\partial^2\theta}{\partial\beta^2} + 2\frac{\partial\theta}{\partial\beta} = \frac{1}{\eta}\frac{\partial\theta}{\partial\eta} + \frac{\partial^2\theta}{\partial\eta^2} + \frac{\partial^2\theta}{\partial\xi^2} + \left(Q + \frac{1}{2}\frac{\partial Q}{\partial\beta}\right) \tag{7}$$

The heating source in its dimensionless form is rewritten as:

For Type I superconductor:

$$\begin{aligned} &Q = 0 &&\text{for} \quad \theta < \theta_{c1} \\ &Q = G_{max} &&\text{for} \quad \theta \geq \theta_{c1} \end{aligned} \tag{8}$$

and for Type II superconductor:

$$\begin{aligned} &Q = 0 &&\text{for} \quad \theta \leq \theta_{c1} \\ &Q = \frac{G_{max}}{f}\frac{\theta - \theta_{c1}}{1 - \theta_{c1}} &&\text{for} \quad \theta_{c1} < \theta < 1 \\ &Q = \frac{G_{max}}{f} &&\text{for} \quad \theta \geq 1 \end{aligned} \tag{9}$$

and equation (6) is reduced to

$$\begin{aligned} &\theta(\xi, \eta, 0) = B &&\text{for} \quad 0 < \xi \leq L, \text{ and } 0 \leq \eta \leq \delta\eta \\ &\theta(\xi, \eta, 0) = 0 &&\text{for} \quad \xi > L, \text{ and } \delta\eta \leq \eta \leq \eta_0 \\ &\frac{\partial\theta(\xi, \eta, 0)}{\partial\beta} = \theta_i, &&\text{for} \quad 0 \leq \xi \leq \infty, \text{ and } 0 \leq \eta \leq \eta_0 \\ &\frac{\partial\theta(\beta, 0, \eta)}{\partial\beta} = 0, &&\theta(\beta, 0, \eta) = 0 \\ &\frac{\partial\theta(\beta, \xi, 0)}{\partial\beta} = 0, &&\frac{\partial\theta(\beta, 0, \eta_0)}{\partial\beta} = -B_i\theta \end{aligned} \tag{10}$$

2.1 Thermal stability criterion

The temperature distribution within the superconductor has the following general form $\theta = \theta(\beta, \xi, \eta, B, R, Q, B_i, L, f, \dot{\theta}_i)$. It is obvious that the superconductor maximum temperature occurs at $\xi = 0$ and $\eta = 0$. The temperature at this location is the largest possible one, as heat needs to transmit across the maximum distance in order to be dissipated through convection on the surface. Thus, if the temperature distribution is stable at this location, then it will be stable elsewhere. This maximum temperature is referred to by θ_1 where $\theta_1 = \theta(\beta, \xi, \eta, B, Q, B_i, L, f, \dot{\theta}_i)$. For each combination of B, Q, B_i, L, $\dot{\theta}_i$ and f two behaviors can be featured; (a) θ drops below 1 which means that the normal zone shrinks to zero and the superconductor is stable and (b) θ does not drop below 1 indicates that the normal zone grows and the superconductor is unstable. We are, in particular, interested in the marginal case when the conditions

$$\theta_1 = 1, \qquad \frac{\partial \theta_1}{\partial \beta} = 0 \tag{11}$$

occur simultaneously. For each combination of B, Q, B_i, L, $\dot{\theta}_i$ and f, we may find the critical value of Q, which is referenced to Q_c, where for each, $Q \leq Q_c$ the two conditions given in equation (11) are satisfied. The stability criterion is then: $Q < Q_c$ for collapse (stable) and $Q > Q_c$ for growth (unstable).

2.2 Solution methodology

The governing equations have been solved numerically by means of FlexPDE program (Ünal *et al.*, 1993). FlexPDE is a software tool for the solution of a system of partial differential equations. It offers an integrated solution environment, including problem description language, numerical modeling, and graphical output of the solution. FlexPDE uses the power finite element method to obtain its numerical solution.

3. Results and discussion

Figure 2 shows a comparison between the results of the numerical code used here with that obtained by Bejan and Tien (1978) for the superconductor stability using the diffusion heat conduction model. The figure shows the variation of the critical Joule heating source with the disturbance intensity B. It is clear from this figure that the predictions of both models are in good agreement.

Figure 3 shows the transient response of the superconductor maximum temperature θ_1 at different heating sources Q for Type II superconductors. It is clear that the stability collapses as the heating source increases.

Figures 4 and 5 show the transient response of the superconductor maximum temperature θ_1 at different Biot numbers (B_i) and for a Type II superconductor. As predicted, it is clear that the stability collapses as the value of Biot number decreases. It is clear that a Type II is more stable than a Type I superconductor. The reason for this advantage of Type II superconductors is its ability to redistribute the current excess to the critical current from the

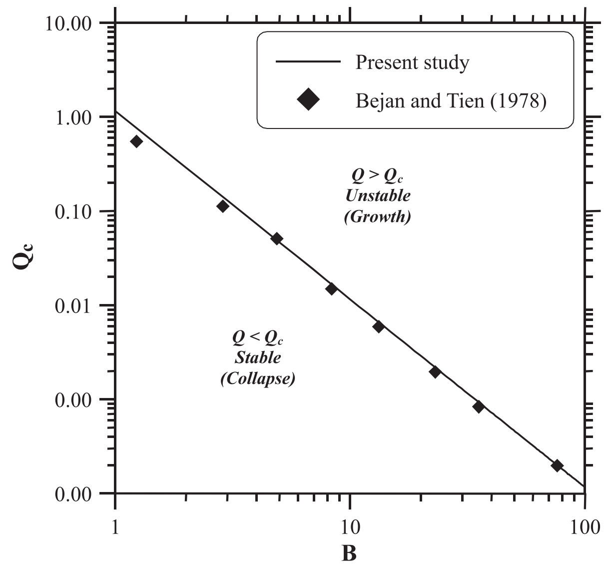

Figure 2.
Comparison between the results obtained in this study and the results reported by Bejan and Tien (1978) for type-superconductor. ($f = 0.5$, $Bi = 0.0$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\tau_i = 0.0$, and $L = 1.0$)

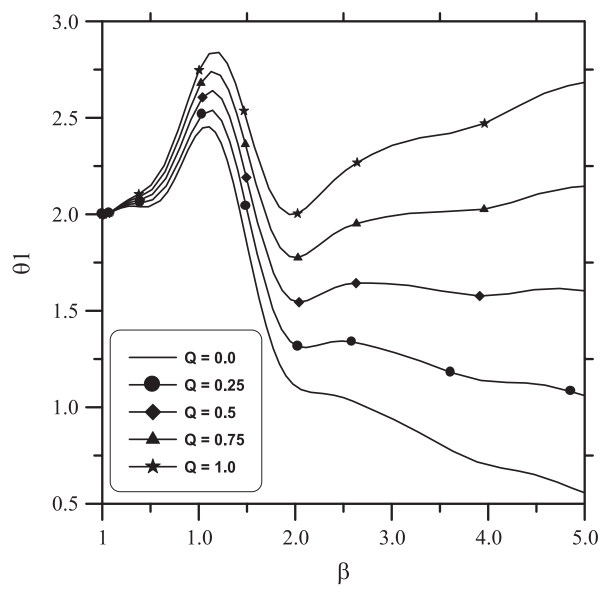

Figure 3.
Effect of dimensionless Joule heating on type-superconductor thermal stability based on the two-dimensional wave model. ($B = 2$, $f = 0.5$, $Bi = 0.18$, $\theta_{c1} = 0.1$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\eta = 0.0$, $\tau_i = 0.0$, and $L = 1.0$)

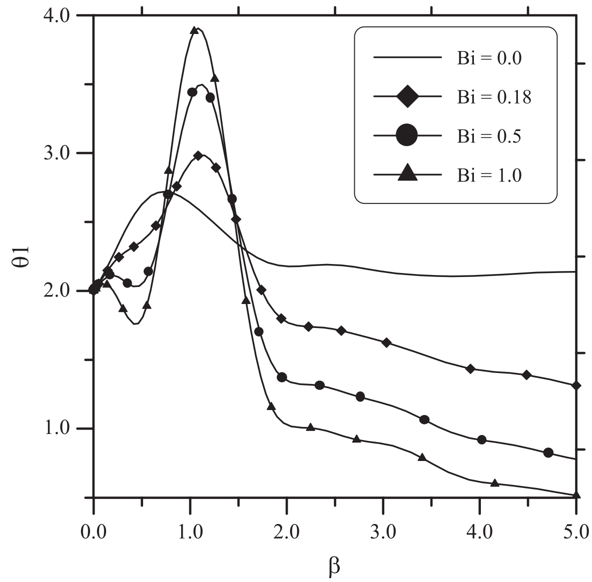

Figure 4.
Effect of Biot number on type-superconductor thermal stability based on the two-dimensional wave model. ($B = 2$, $f = 0.5$, $Q = 0.25$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\tau_i = 0.0$, and $L = 1.0$)

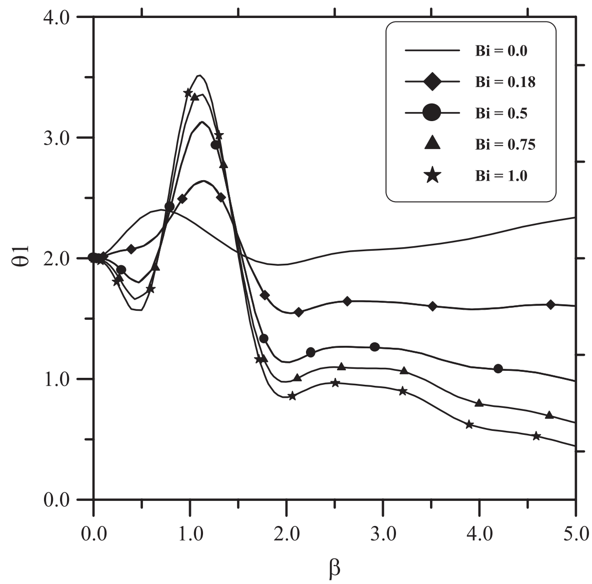

Figure 5.
Effect of Biot number on type-superconductor thermal stability based on the two-dimensional wave model subjected. ($B = 2$, $f = 0.5$, $Q = 0.5$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\eta = 0.0$, $\tau_i = 0.0$, and $L = 1.0$)

superconductor into the metal matrix within the normal zone. This, in turn, minimizes the Joule heating effect through the superconductor.

Figures 6 and 7 show the axial temperature distribution at different times and for Type II under the effect of a two-dimensional parabolic and hyperbolic heat conduction models. It is clear from these figures that the wave model predicts a sharp discontinuity in the axial temperature distribution. It is clear from Figure 7 that this discontinuity vanishes as time proceeds. Furthermore, Figures 6 and 7 shows that diffusion model underestimate the temperature at the early stages of time and overestimates it at large time.

Figures 8 and 9 show the transient response of the superconductor maximum temperature θ_1 at different initial disturbance lengths L and for Type I and Type II superconductors. As predicted, the stability collapses as the disturbance length increases. These two figures provide another evidence that Type II is more stable than Type I.

Figure 10 shows the transient response of the superconductor maximum temperature θ_1 at a different disturbance duration time τ_i and for Type I superconductors. The parameter τ_i represents the dimensionless disturbance duration time which is the time within which a fixed imposed initial temperature B is maintained within the normal zone. In other words, τ_i represents the time within which the initial condition in the normal zone remains valid. As predicted, the stability collapses as this time increases.

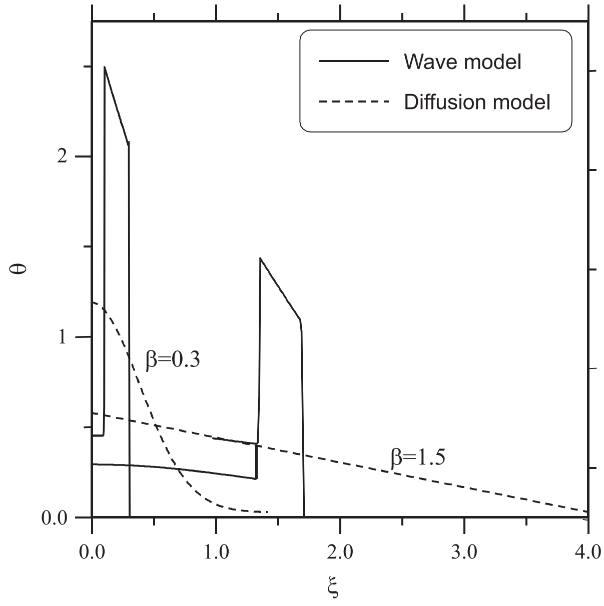

Figure 6.
Comparison between temperature profiles obtained based on diffusion model and wave model for type-superconductor. ($B = 2$, $f = 0.5$, $Q = 0.0$, $Bi = 0.25$, $\theta_{c1} = 0.1$, $\dot{\theta} = 0.0$, $\tau_i = 0.0$, $\eta = 0.0$, and $L = 0.15$)

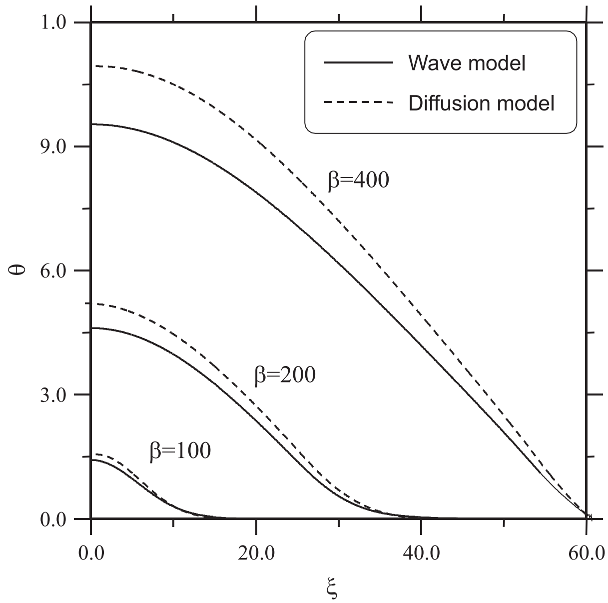

Figure 7.
Comparison between temperature profiles obtained based on diffusion model and wave models for type-superconductor. ($B = 2$, $f = 0.5$, $Q = 1$, $Bi = 0.18$, $\theta_{c1} = 0.1$, $\dot{\theta} = 0.0$, $\tau_i = 0.0$, $\eta = 0.0$, and $L = 1.5$)

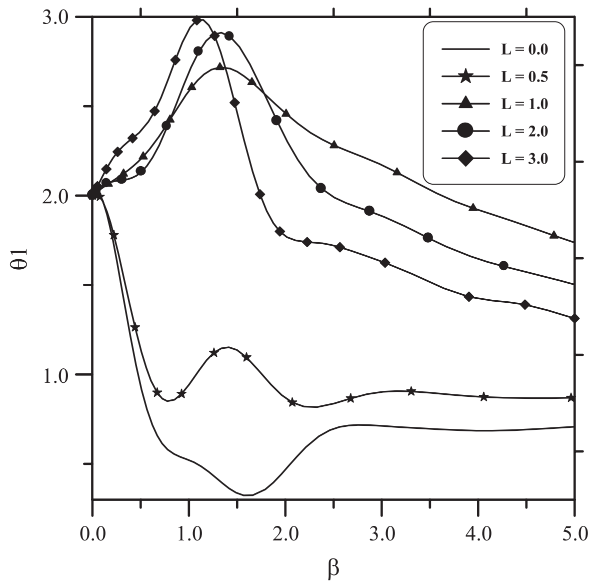

Figure 8.
Effect of dimensionless disturbance length on type-superconductor thermal stability based on the two-dimensional wave model. ($B = 2$, $f = 0.5$, $Q = 0.25$, $Bi = 0.18$, $\theta_{c1} = 0.1$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\eta = 0.0$, and $\tau_i = 0.0$)

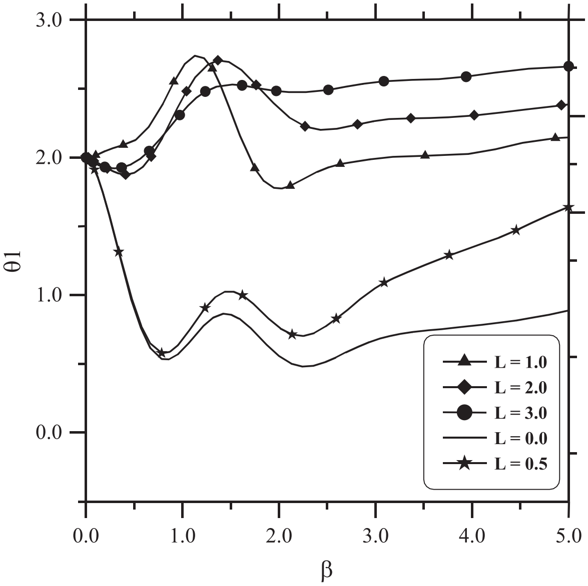

Figure 9.
Effect of dimensionless disturbance length on type-superconductor thermal stability based on the two-dimensional wave model. ($B = 2$, $f = 0.5$, $Q = 0.75$, $Bi = 0.18$, $\theta_{c1} = 0.1$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\eta = 0.0$, and $\tau_i = 0.0$)

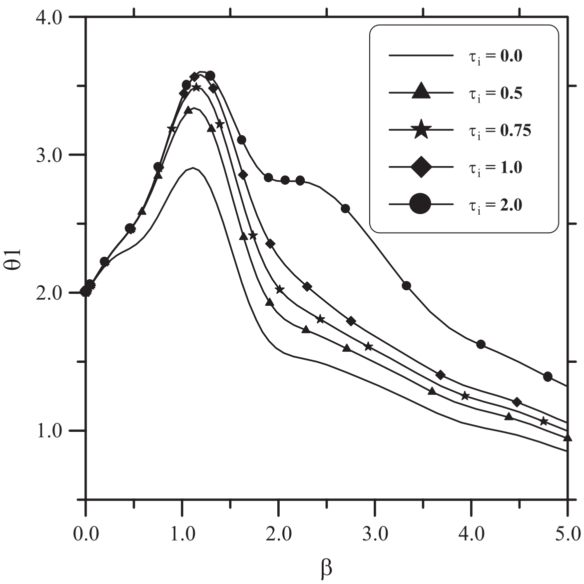

Figure 10.
Effect of dimensionless disturbance duration time on type-superconductor thermal stability based on the two-dimensional wave model. ($B = 2$, $Q = 0.0$, $Bi = 0.18$, $\xi = 0.0$, $\eta = 0.0$, and $L = 1.0$)

Figure 11 shows the transient response of the superconductor maximum temperature θ_1 at different current sharing temperatures θ_{c1} and for Type II superconductors. It is clear that as the current sharing temperature decreases, the stability collapses. However, this effect is insignificant. This is obvious since as θ_{c1} increases, the superconductor can sustain a localized thermal disturbance having a higher temperature before entering the normal zone.

Figures 12 and 13 show a stability map in terms of the critical Joule heating Q_c and the disturbance intensity B for both superconductor types and using the two heat conduction models. It is clear from this figure that the hyperbolic model predicts a wider stable region as compared to the predictions of the diffusion heat conduction at large values of B and Bi. On the other hand, the diffusion model predicts a wider stable region in the limit of small values of B. Also, the two models predict a linear relation between Q_c and B. The deviations between the predictions of the two models vanish as the Biot number increases. It is obvious that as B increases, the conductor ability to sustain Q_c, while remaining stable decreases. Also, it is clear from these two figures that the stability region for Type II superconductors is wider than that of Type 1. The deviations among the two models vanish as B increases. The effect of Biot number is insignificant at small values of B.

Figure 14 shows the transient response of the superconductor maximum temperature θ_1 at different time-rates of change $\dot{\theta}_i$ of the disturbance initial temperature. As predicted the stability collapses as $\dot{\theta}_i$ increases.

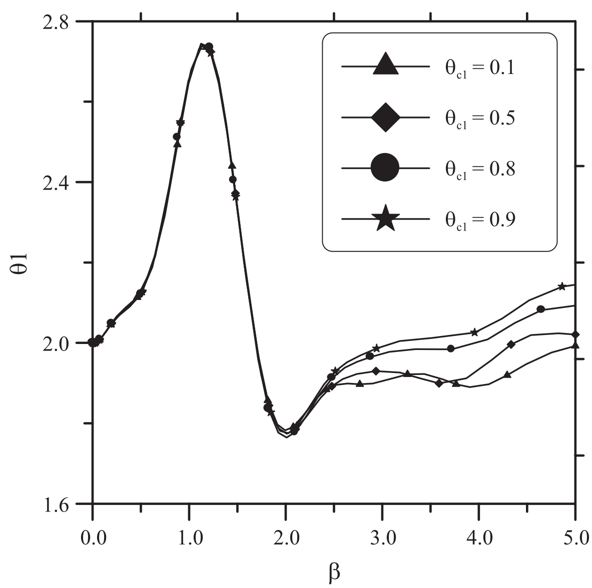

Figure 11.
Effect of dimensionless current sharing temperature on type-superconductor thermal stability based on the two-dimensional wave model subjected to stepwise disturbance. ($B = 2$, $Q = 0.75$, $Bi = 0.18$, $f = 0.5$, $\dot{\theta} = 0.0$, $\xi = 0.0$, $\eta = 0.0$, $\tau_i = 0.0$ and $L = 1.0$)

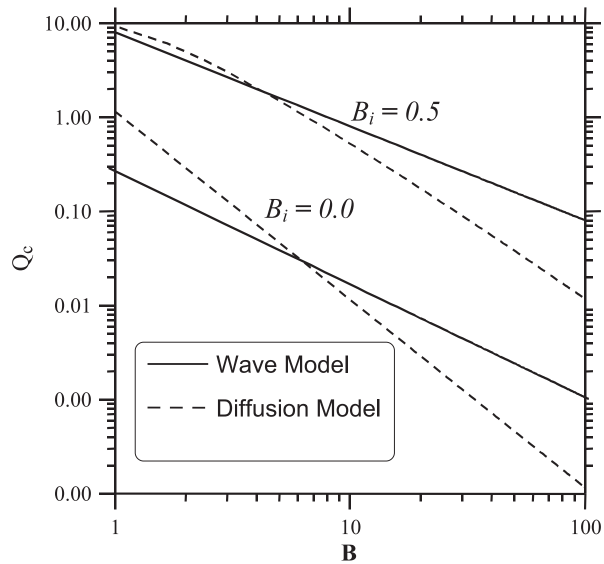

Figure 12.
The stability criterion for type-superconductor based on two different two-dimensional heat conduction models. ($f = 0.5$, $\theta_{c1} = 0.1$, $\dot{\theta} = 0.0$, $\tau_1 = 0.0$, $\xi = 0.0$, $\eta = 0.0$, and $L = 1.0$)

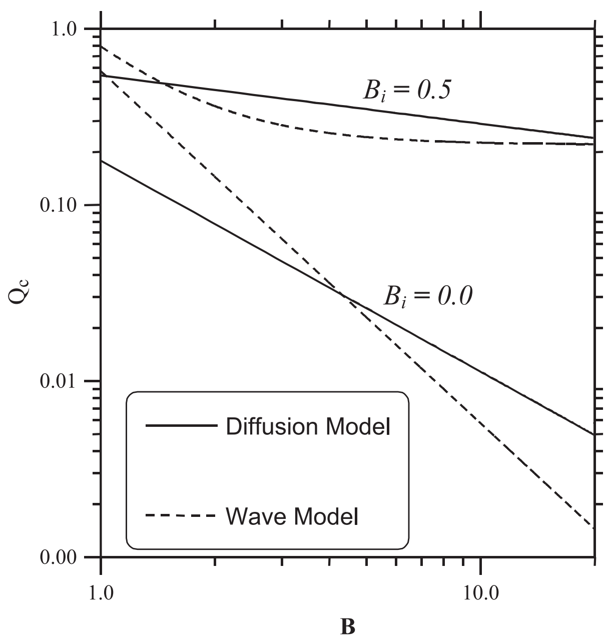

Figure 13.
The stability criterion for type-superconductor based on two different two-dimensional heat conduction models. (For $\dot{\theta} = 0.0$, $\tau_1 = 0.0$, $\xi = 0.0$, $\eta = 0.0$, and $L = 1.0$)

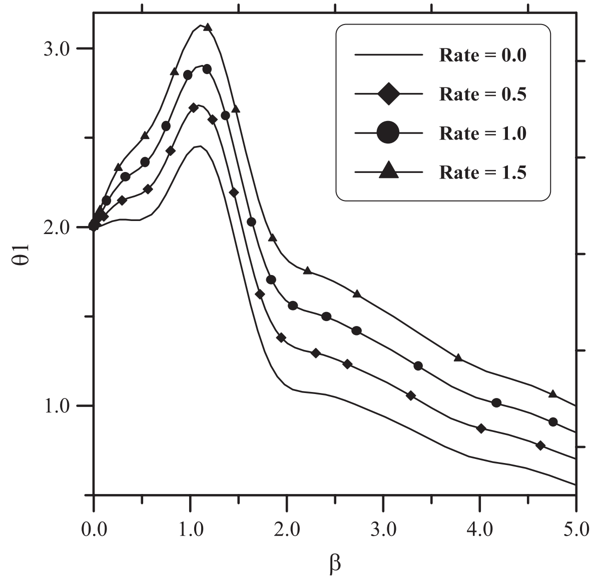

Figure 14.
The effect of initial time-rate of temperature ($\dot{\theta}$) on type-superconductor thermal stability based on the two-dimensional wave model. ($B = 2$, $Q = 0.0$, $Bi = 0.18$, $f = 0.5$, $\theta_{c1} = 0.1$, $\tau_i = 0.0$, $\xi = 0.0$, $\eta = 0.0$, and $L = 1.0$)

4. Concluding remarks

The superconductor thermal stability is investigated under the effect of the two-dimensional hyperbolic heat conduction model. The parameters which are found to affect the superconductor thermal stability are the disturbance intensity B, volume fraction of the stabilizer f, initial disturbance length L, Biot number Bi, Joule heating source Q, current sharing temperature θ_{c1}, rate of change of the initial temperature $\dot{\theta}_i$ and the disturbance duration time τ_i. It is found that the two-dimensional hyperbolic model predicts a wider stable region as compared to the predictions of the parabolic conduction model. As predicted, the study shows that a Type II superconductor is more stable than for Type I. The superconductor stability improves as L, B, τ_i, $\dot{\theta}_i$ and Q decrease and as Bi,and θ_{c1} increase. However, the effect of the current sharing on the superconductor stability is insignificant.

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